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TITLE: NEUTRINO-ELECTRON SCATTERING AT LAMPF
----LARGE CHERENKOV DETECTOR EXPERIMENT

AUTHOR(S): D. Hywel White

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MASTER

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

NEUTRINO-ELECTRON SCATTERING AT LAMPF
----LARGE CHERENKOV DETECTOR EXPERIMENT

D. Hywel White

Los Alamos National Laboratory

Los Alamos, NM 87545

Abstract

An experiment to measure neutrino-electron scattering is described. The neutrinos are generated in a beam stop from 800 MeV protons at LAMPF. The expected precision on $\sin^2\theta_W$. The expected precision on $\sin^2\theta_W$ is 1%. The experiment also gives stringent hints on neutrino oscillations and is sensitive to neutrinos from supernora collapse.

Introduction

The Standard Model of electroweak interactions seems presently to be in excellent shape. Measurements of the masses of W and Z, deep inelastic-neutrino scattering and other less precise data have been amenable in a global analysis[1] to a description in terms of a single value of $\sin^2\theta_w$ after radiative corrections have been made, regardless of reaction and momentum transfer. It is widely believed that the three-family structure of quarks and leptons is correct, and with this assumption the only serious uncertainty in the calculation of radiative corrections arises from the top-quark mass. Apart from this uncertainty, the theoretical precision is considerably better than any likely experimental accuracy in the near future. This paper describes an experiment to extend the precision with which the Standard Model can be tested in a regime where accuracy has been difficult to achieve in the past. Neutrino-electron scattering is theoretically clean, even at the one-loop level, and tests the electroweak theory in a way complementary to tests made at the Z pole. We also note that the present best values for $\sin^2\theta_w$ in neutrino-electron scattering come from the Brookhaven experiment and from CHARM at CERN. The Brookhaven number is

$$\sin^2\theta_w = 0.195 \pm 0.018 \pm 0.013 \quad [2]$$

and the CHARM II preliminary result reported at the Munich conference is also lower than the global value of 0.230 from Ref. 1. A top-quark mass higher than 45 GeV, which is commonly used for no good reason, would go some way to explain this discrepancy.

In cartoon style, the radiative corrections to the mass of the Z are described by Fig. 1.

Figure 1.

These one-loop corrections can be separated into contributions from leptons, quarks, and bosons. The leptonic contribution (0.0328) is well specified since all the lepton masses are known to sufficient precision; the largest uncertainty in the quark loop contribution is the top-quark mass, which varies as $(m_t/m_W)^2$. The bosonic contribution, for example from the Higgs, is relatively small. Assuming that the top-quark mass is 45 GeV the total radiative correction to the vector-boson mass is 0.0713 ± 0.0013 where the error derives from uncertainty in input data to the theoretical calculation. If the top-quark mass is known, then this error represents a limit to tests of the electroweak theory, at this time, it also represents a goal that the experiments can try to attain. If the top mass is not known then the triad of measurements at the Z pole, the ratio of W and Z masses, and neutral-current scattering can attempt to define the top mass and verify that the radiative corrections are consistent with three families.

The neutrino Z vertex can only be reached with any degree of precision from neutrino-neutral-current scattering. The diagram in Figure 1. is typical of a set of one-loop corrections to neutrino scattering, which must be verified to complete the test of the electroweak theory at this level. At present the most accurate tests of neutral currents are the deep-inelastic-scattering experiments, which along with measurements of the boson masses dominate the global fit referred to earlier. The quality of this fit has been interpreted as limiting the top-quark mass to below 180 GeV.

Experimental Method

Neutrino-electron-scattering measurements in the recent past have concentrated on measurements of the ratio of ν_μ to $\bar{\nu}_\mu$ electron scattering. The experiments rely on changing the helicity of the neutrino beam through the focusing system and normalization is accomplished using a known reaction, quasi-elastic scattering.

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Systematic errors arise in the use of two slightly different beams and reactions for normalization. The LAMPF proposal is to measure the ratio

$$R = \frac{\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-)}{\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-) + \sigma(\nu_e e^- \rightarrow \nu_e e^-)} .$$

Neutrinos in the numerator arise from π^+ decay, and in the denominator from μ^+ decay. The ratio of the flux in the numerator to that in the denominator is the same to better than 1%, with a difference only in that 1% of the pions decay in flight and the subsequent neutrinos miss the detector because they are boosted to the forward direction, but the muons from π^+ decay all come to rest and decay isotropically. The shape of the spectra is shown in Fig. 2.

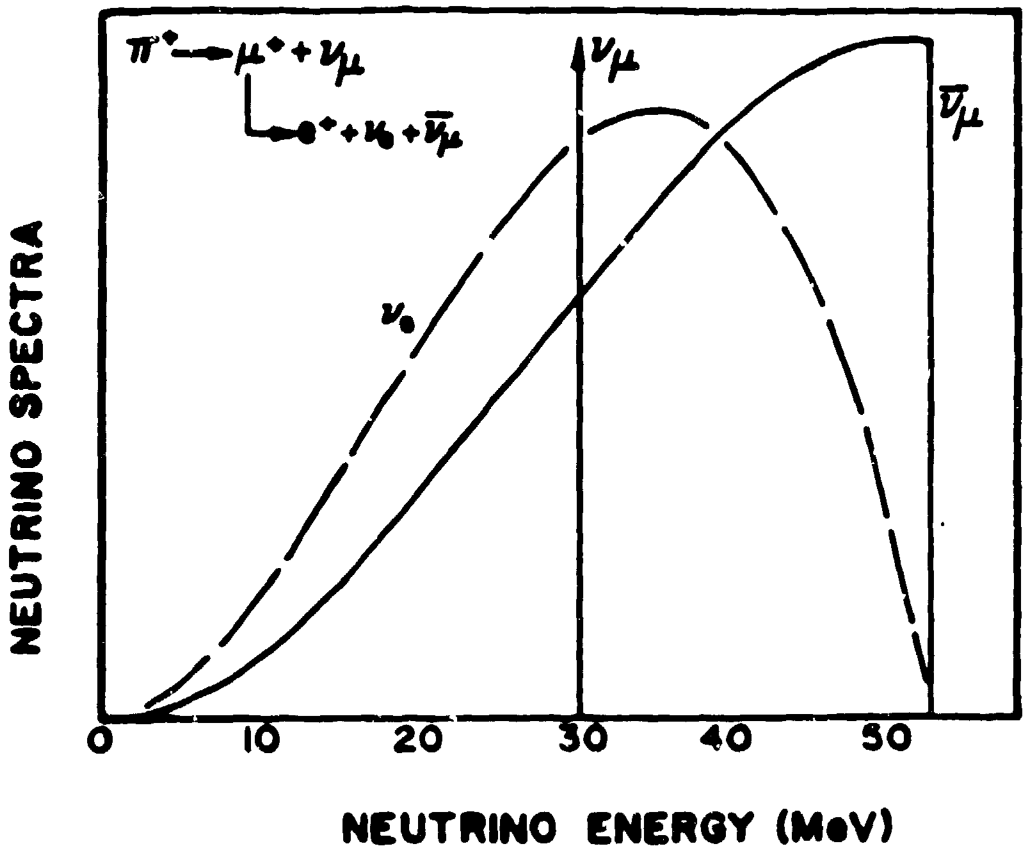

Figure 2.

They are probably among the best known spectra in physics. The delta function from π^+ decay has a "width" given by the ratio of atomic energy scales divided by 30 MeV and allows the possibility of a y measurement with excellent resolution. The separation of π^+ decay and μ^+ decay is made possible by a compressor ring that we shall describe below. The proton spill from this ring is approximately 250 ns, long compared to the pion lifetime and short compared to the muon lifetime, giving a time dependence of neutrino flux shown in Fig. 3.

In Fig 4. we show a schematic of the beam-delivery system.

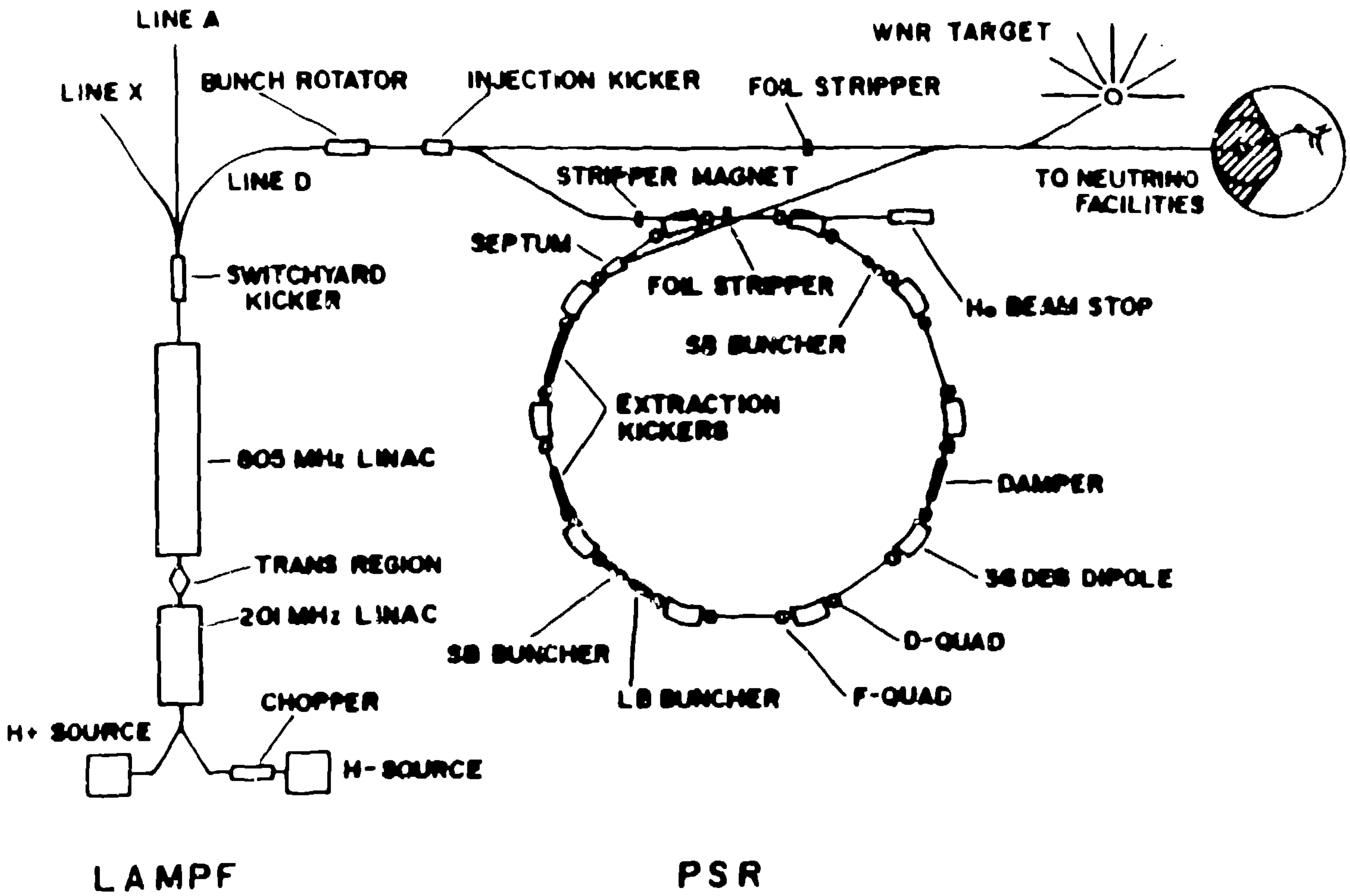

Figure 4.

The linac normally accelerates H^- ions to 800 MeV, which are injected into the proton storage ring (PSR) used as a compressor ring. The beam is chopped so that the ring has an empty space for clean single-turn extraction giving a proton spill that is typically 250 ns in duration. This beam is transported to a beam stop in the center of a detector shown schematically in Fig. 5.

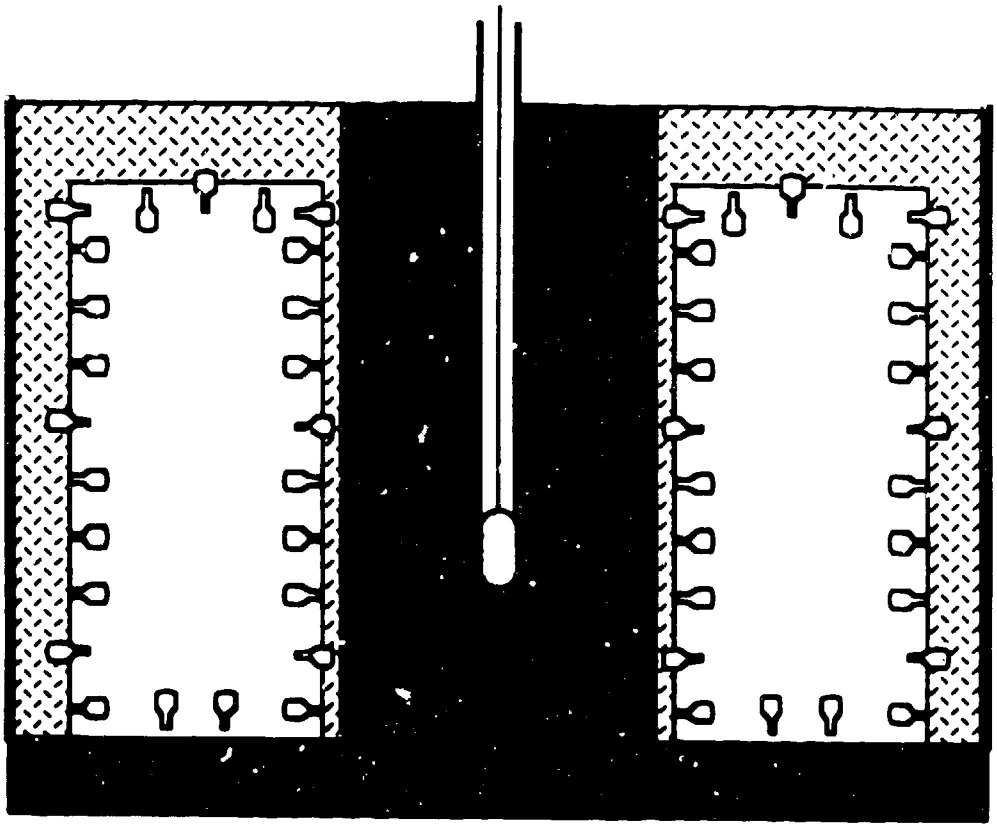

Figure 5. **NOT TO SCALE**

At these proton energies, the predominant background is from neutrons and by far the most cost-effective shield is steel. The target is made mainly of copper, and the pions are made and stop in the same material. Typically, the pions go about 10 cm in the copper before coming to rest and decay in the case of π^+ and are absorbed in the case of π^-. Only one-sixth as many π^- as π^+ are made by the protons, and of these only 1% decay in flight and are not absorbed. At LAMPF, the neutrinos from the beam stop form a very clean isotropic source of time-separated ν_μ and $(\nu_e + \bar{\nu}_\mu)$.

The proton beam, after extraction from the PSR, is transported to the detector area and bent through 90° into the vertical beam stop. In Fig. 6 is shown a drawing of the detector and beam stop with dimensions in meters. The iron thickness is adequate for attenuation of the neutrons to an acceptable level.

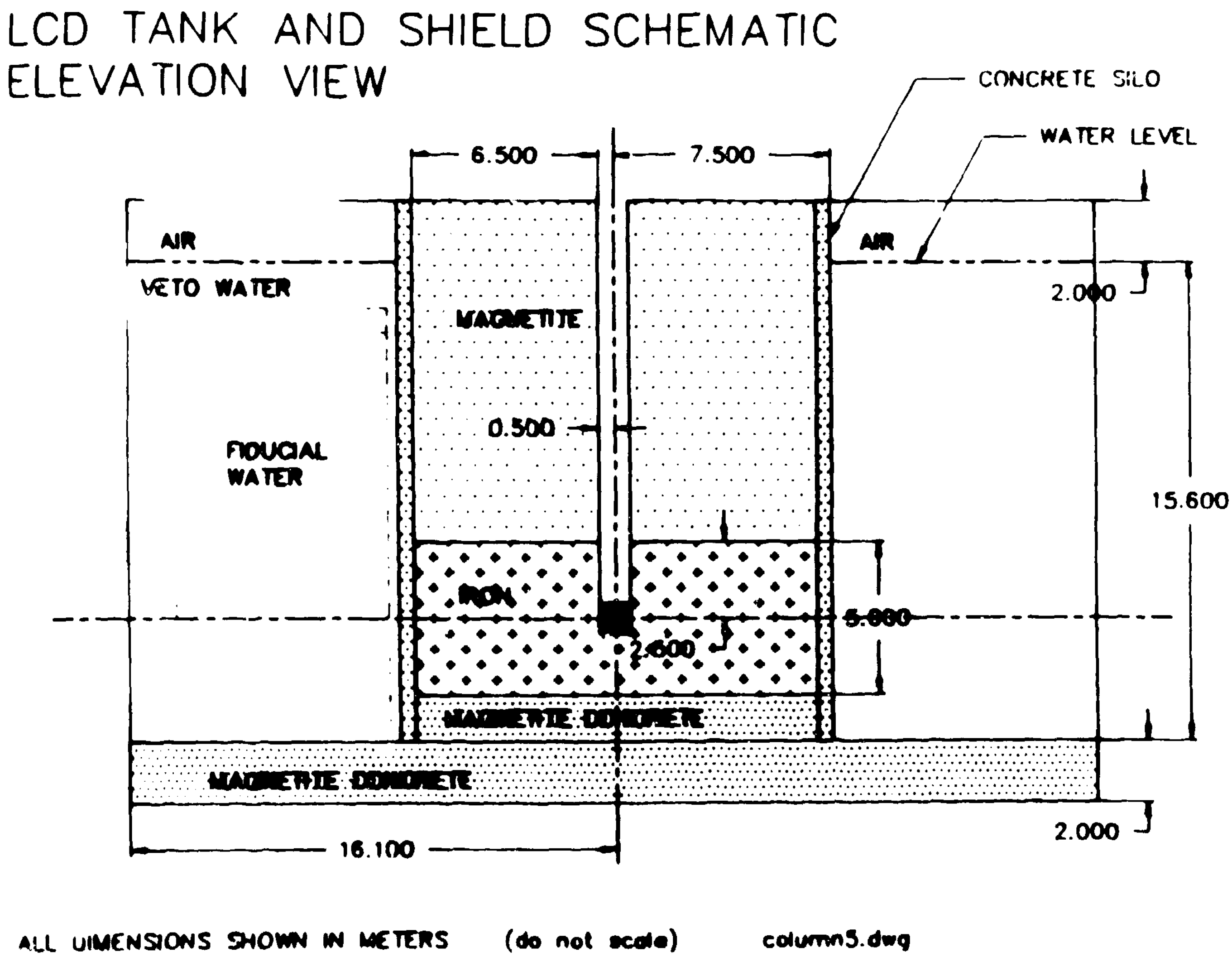
LCD TANK AND SHIELD SCHEMATIC
ELEVATION VIEW
CONCRETE SILO
WATER LEVEL
6.500
7.500
AIR
AIR
VETO WATER
2.000
MAGNETITE
0.500
FIDUCIAL WATER
15.600
IRON
2.600
MAGNETITE CONCRETE
MAGNETITE CONCRETE
2.000
16.100
ALL DIMENSIONS SHOWN IN METERS (do not scale) column5.dwg

Figure 6.

An isometric drawing of the entire system is shown in Fig. 7.

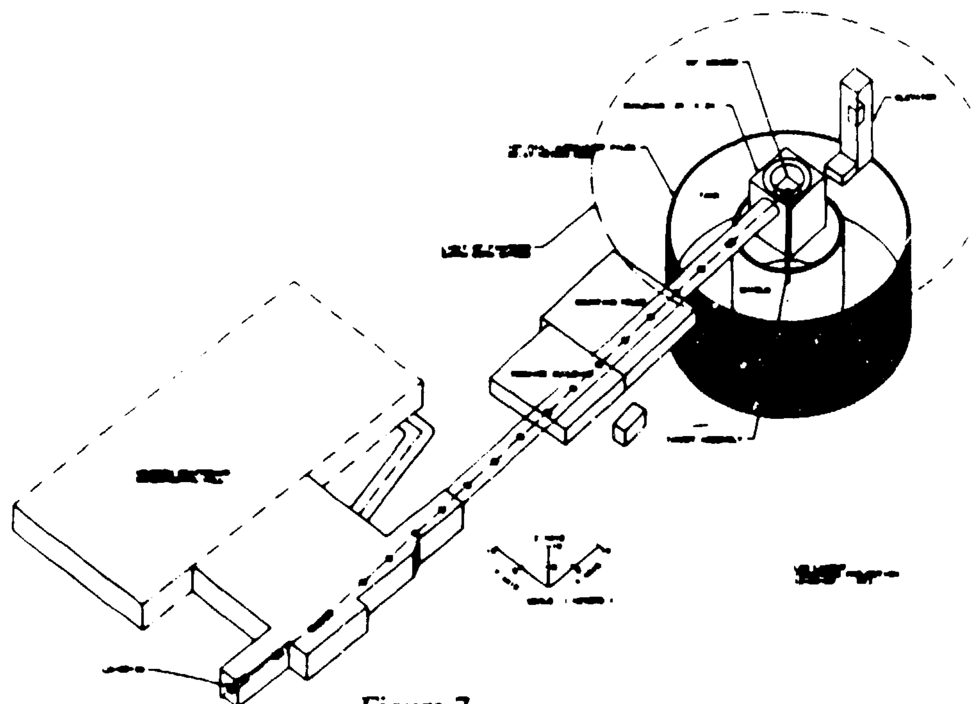

Figure 7.

The active medium in the detector is water, with Cherenkov light from the recoil electrons detected with substantial phototube coverage following the design of the Kamioka nucleon-decay detector. Water is a particularly good medium in this application because it combines adequate energy and angular resolution for low-energy electrons at low relative cost. In Fig. 8 is shown 20 12-MeV Monte Carlo generated

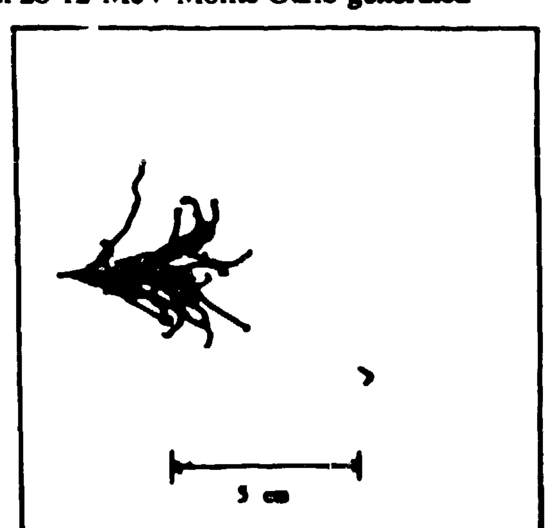

Figure 8.

electron events in water and it is clear that, although the electron preserves the initial direction to a great extent, the precision required to extract the angular information is not great. The energy resolution in a water Cherenkov detector is also adequate providing that a relative photocathode coverage greater than 15% can be achieved. In Fig. 9 is shown a stopping muon event from the Kamioka detector the decay electron can also be clearly seen; this represents a typical event for neutrino-electron scattering.

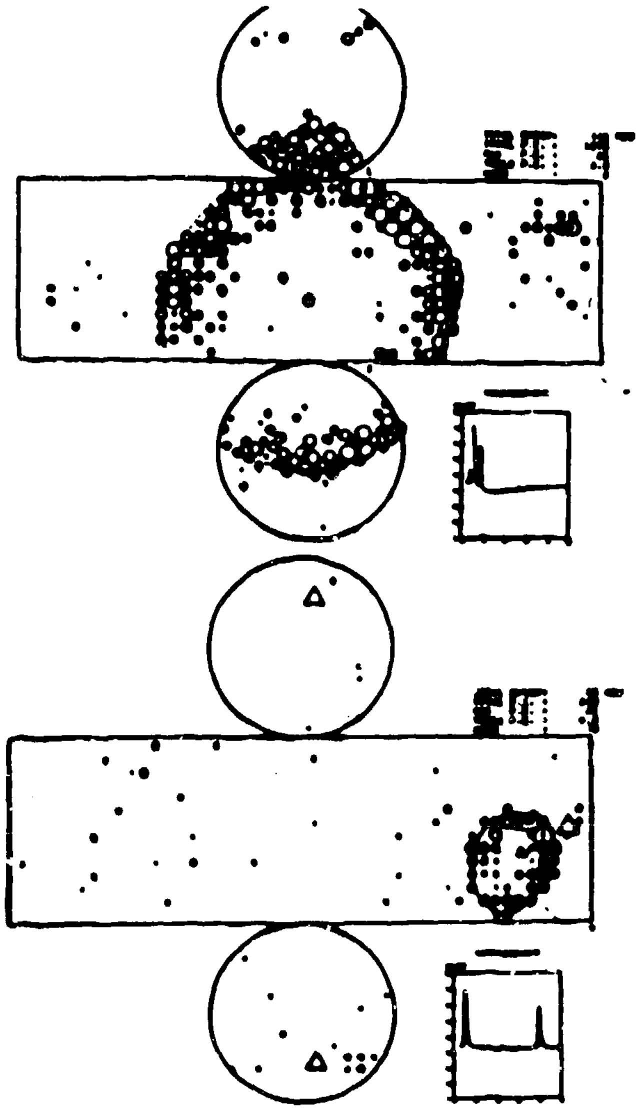

Figure 9.

It is necessary to calibrate the detector absolutely in energy to establish the energy threshold for the experiment and the slightly different efficiency for the numerator and denominator of the measured ratio. Again from Kamioka, we show a Michel spectrum from muon decay in Fig. 10. The energy scale was established by using a Cf - Ni source, which is a known gamma-ray source around 9 MeV. With this energy calibration the Monte Carlo match to the data in Fig. 10 is remarkable, given that there is

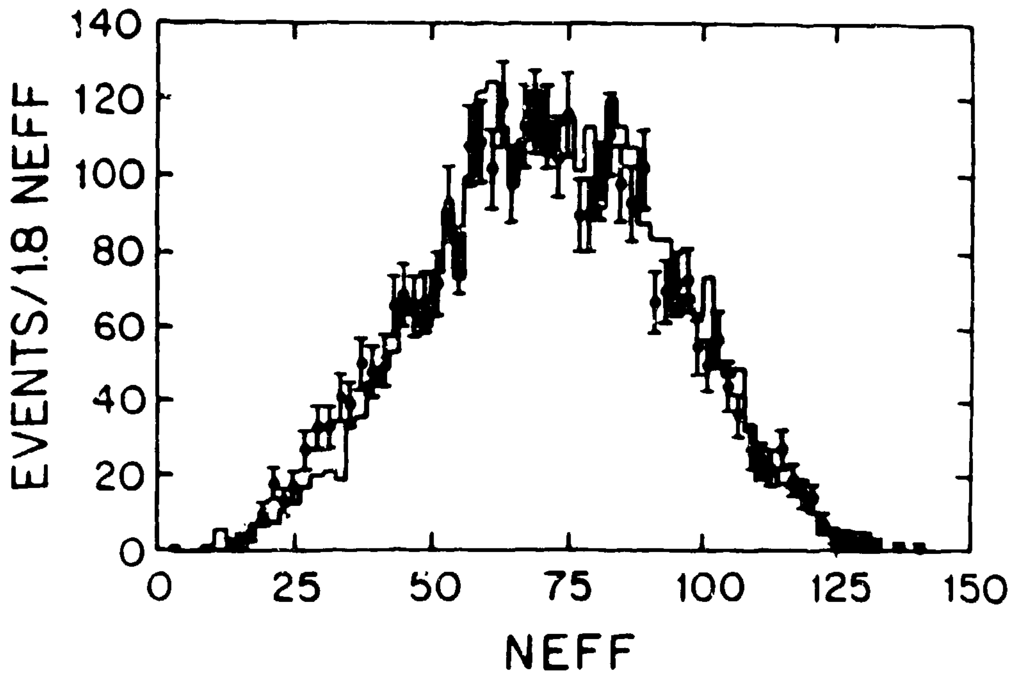

Figure 10.

no further adjustment to the energy scale. The Kamioka experiment establishes the absolute energy scale to better than 3% by this method.

Experimental Precision

The number of neutrino-scattering events shown in Table I reflects three years of normal LAMPF beam time (3000 Hrs/yr) with half of the accelerated H^- ions injected into the PSR.

Table I

Events	ν_μ	ν_e	$\bar{\nu}_\mu$
Generated in Sensitive region	16330	105470	17447
Reconstructed in the Fiducial region	10450	71265	11440
P.E. > 27	7524	54570	8505

With this degree of statistical precision, the requirements for systemic precision also become severe. In Table II is shown a list of the dominant systematic errors. By measuring the ratio of cross sections in real time, it is clear that substantial cancellation of systematic errors occurs. However, to achieve 1% accuracy on $\sin^2\theta_W$, systematic errors are still important.

Table II

	Cause	Error in %
1.	Decay in Flight	0.12
2.	Cosmic Rays	0.01
3.	ν_e - O	0.50
4.	Prompt γ and $\pi^{\pm}$ from neutron interactions	0.65
5.	Delayed e from n-induced π^+ decay	0.01
6.	Measurement of PSR spill shape	0.15
7.	Systematic time shift	0.08
8.	Absolute threshold energy	0.40
9.	Nonuniform efficiency	0.10
	Total systematic error	0.94 (added in quadrature)
	Total statistical error	1.60
	Total error in R	1.86
	Total error in $\sin^2\theta_W$	0.89

Other Measurements

This experiment has been designed to perform a measurement of neutrino-electron scattering as a critical test of the electroweak theory; the facility is sufficiently versatile, however, that a number of other tests may be performed. We discuss them briefly below.

The neutrino flux from the beam stop is known to about 5% presently from calculation and subsidiary measurements. It is expected that this uncertainty can be reduced by about a factor of two by improvements in the input-particle-production data and appropriate subsidiary measurements. With this information, the absolute cross sections can be determined for ν_μ and ν_e scattering. If the neutrino has a magnetic moment, the electron-scattering cross section is enhanced by

$$\Delta\sigma = \pi\alpha^2/m_e^2 \, f^2 \, [\ln(E_\nu/E_e^{min}) - 1 + E_e^{min}/E_\nu]$$

$$\pi\alpha^2/m_e^2 = 2.49 \times 10^{-25} \text{ cm}^2.$$

The enhancement is almost energy-independent in contrast to the electroweak prediction , which varies linearly with energy. It is expected that the cross section will be measured to 3% , and also that the relative effect of a magnetic moment is greater than at 1 GeV where the best present limit has been obtained. This limit of 0.85×10^{-9} bohr magnetons is expected to improve by a factor of 10 to 20. The charged-radius limit is proportional to energy as is the Standard Model cross section so that $< r^2 >$ is expected to improve by about a factor of five.

As was emphasised above, $\bar{\nu}_e$ are produced about 0.1% of the time in the beam stop. The dominant reaction by which $\bar{\nu}_e$ interact is

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

on free protons in the water. The predominant process by which electrons appear at wide angles from the neutrino direction is

$$\nu_e + {}^{16}O \rightarrow e^+ + {}^{16}F$$

where the electron energy is limited to 30 MeV. The basic strategy of an oscillation search from the beam stop is to search for electrons of energy greater than 30 MeV at wide angles to the neutrino direction. This is presently being done in experiment E645 at LAMPF. This oscillation search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ will be limited by the background reaction

$$\nu_e + {}^{18}O \rightarrow e^{+} + {}^{18}F$$

with ^{18}O at 0.2% of normal oxygen in water. The background level will conservatively limit sensitivity at the levels shown in Fig. 11.

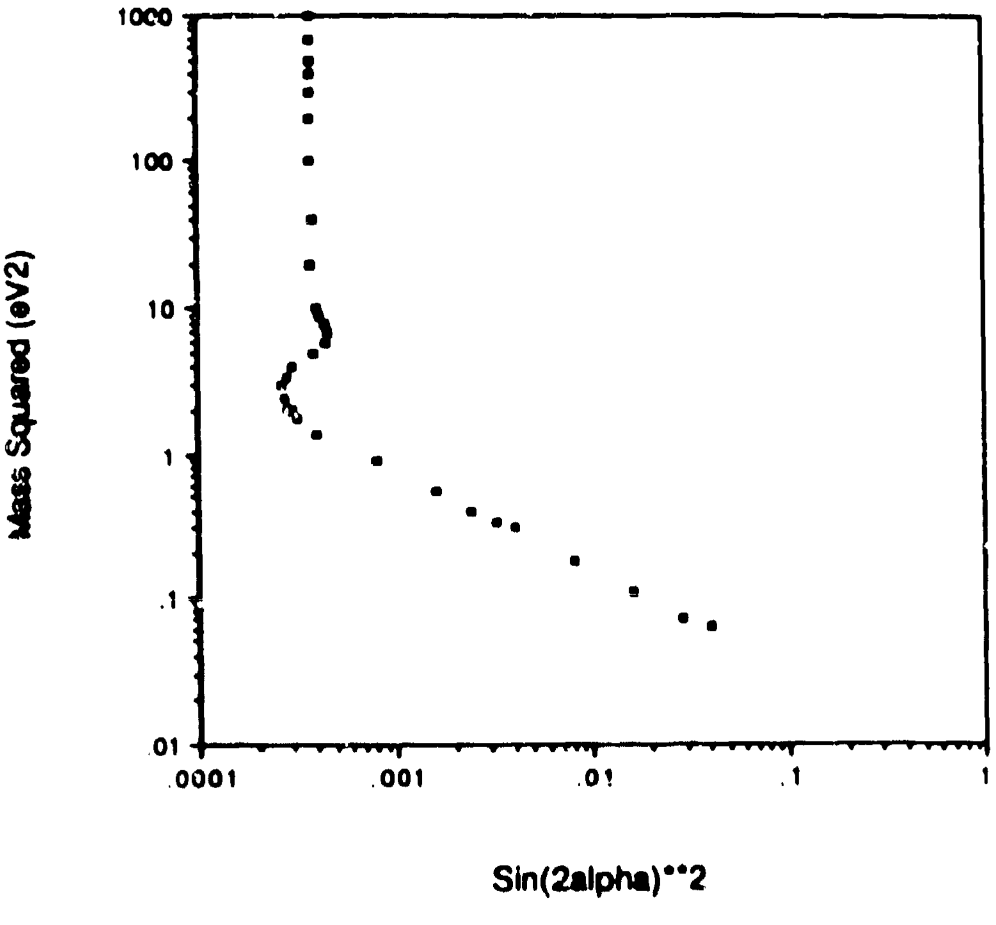

Figure 11.

There are a series of other oscillation constraints that emerge from this experiment from a distortion of the ratio R if $\nu_\mu \rightarrow \nu_e$, arising from the fact that neutral-current scatterings of these two neutrinos differ by a factor of six. In the neutral-current sector this experiment is insensitive to $\nu_\mu \rightarrow \nu_\tau$ oscillations because the two cross sections are equal. The radial dependence of the charged-current cross section also gives a disappearance limit for ν_e with the sensitivity peaking at about 3 eV^2. Each of these possibilities is described in detail in Ref. 3.

The charged-current cross section on ^{16}O has also become of interest recently with the possibility that discrepancies in the abundance of light elements can be resolved by postulating effects due to neutrino interactions in supernovae[4]. The absolute cross section measured in this experiment is an important constraint on these models.

Solar neutrino detectors have been proposed[5], which rely on the charged-current cross section

$$\nu_e + D \rightarrow e^+ + n + n.$$

Although this cross section is relatively amenable to calculation, it would clearly be of interest to measure it directly as could be done by inserting a transparent enclosing vessel for deuterium in the style of the experiment of Ref. 5.

This detector is an excellent supernova detector, using the neutrino interactions as in the Kamioka and IMB detectors. It turns out that the rate of electrons from a supernova of the intensity of SN1987A is in excess of the rate for the normal experiment so that if the challenge of data acquisition can be surmounted, this experiment would be more sensitive than Kamioka by about a factor of two. It is not necessary to bury the detector deeply for supernova neutrino detection.

It is tempting to go on listing the opportunities that a flavor-separable calibrated source of neutrinos offers but perhaps enough has been said. Clearly we are very excited that this opportunity exists and hope that this physics appears in a timely fashion.

Acknowledgements

We have reproduced data from Kamioka. We thank that collaboration for making them available. The collaboration proposing this detector is listed in Ref. 3.

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